On the theory of

Quantum Fluids of Light

Part 3/3

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Part 4:

The future:

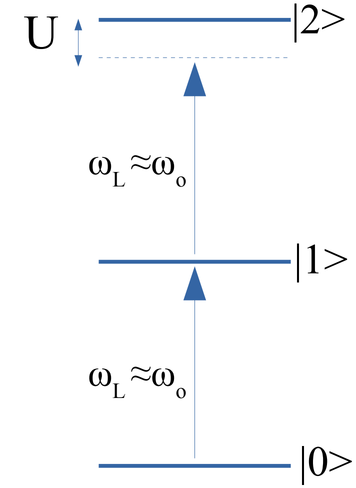
Strongly interacting fluids of light

Mott insulators &
Fractional Quantum Hall liquids

Photon blockade

Driven-dissipative Bose-Hubbard model:

$$H_0 = \sum_i \hbar\omega_o \hat{b}_i^\dagger \hat{b}_i - \hbar J \sum_{\langle i,j\rangle} \hat{b}_i^\dagger \hat{b}_j + \hbar \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1) + \sum_i F_i(t)\, \hat{b}_i + h.c.$$

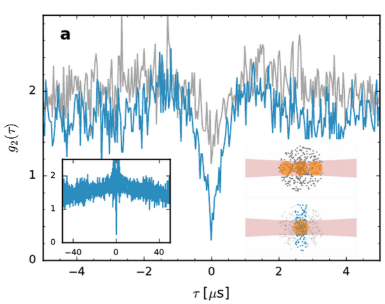


- Array of single-mode cavities at ω_o , tunnel coupling J , losses γ
- Polariton interactions: on-site interaction U due to optical nonlinearity
- If U >> γ & J, coherent pump resonant with 0→1, but not with 1→2.

Photon blockade → Effectively impenetrable photons

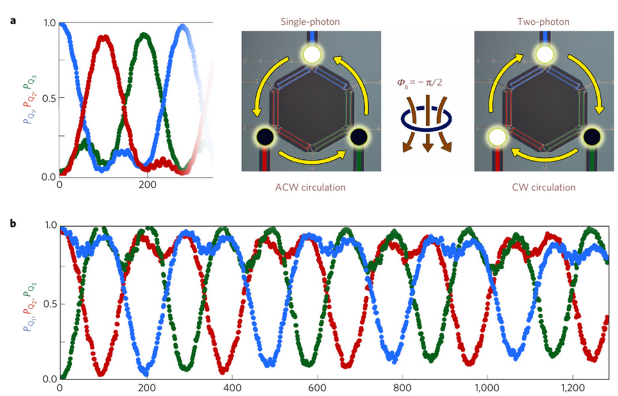
Opposite regime than non-interacting photons of Maxwell's eqs.

Single-cavity blockade observed in many platforms since the 2000s, present challenge → scale up to many-cavity geometry

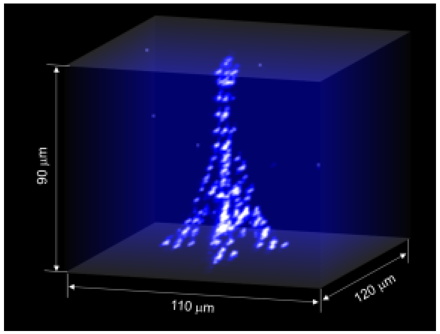


Polariton blockade via Rydberg-EIT (@ Chicago)

Circuit QED device (@GoogleLabs)

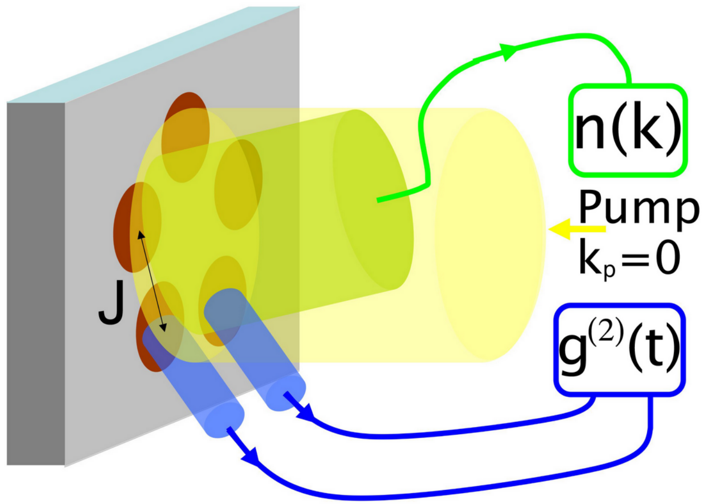


Fluid of spin excitations in lattice of Rydberg atoms. (Broways, Lukin,...)



IC-Ciuti, *Quantum Fluids of Light*, RMP **85**, 299 (2013)

1D array of coupled cavities



- generalized Bose-Hubbard model
- Polariton interactions: strong on-site repulsion U
- Tunneling: Josephson coupling J
- Incident laser: coherent external driving F_p
  - monochromatic at ω_p , plane wave $k_p=0$
- Weak losses $\gamma \ll J, U$ crucial to determine non-equilibrium steady-state
- Light collected in reflection and/or transmission geometry
  - far-field emission: k-selection from orbital angular momentum
  - near-field emission: spatial resolution
- Strongly interacting regime $J \ll U$

Impenetrable bosons (U=∞): Girardeau's Bose-Fermi mapping

Many-body, bosonic wavefunction written in terms of non-interacting Fermions

$$\psi(x_1, x_2, \ldots) = \epsilon[\sigma(x_1, x_2, \ldots)]\, \psi_F(x_1, x_2, \ldots)$$

✓ density and density fluctuations preserved in Bose-Fermi mapping

✗ coherence function $g^{(1)}(x,x')$ and momentum distribution not preserved

Many-body states labeled by momenta q of occupied Fermi orbitals $|q_1, q_2, q_3 \ldots\rangle$

Periodic boundary cond.: Fermi orbitals satisfy PBC/anti-PBC for odd/even N

Energy (and momentum) preserved by mapping $E = \sum_i \frac{\hbar^2 q_i^2}{2m}$

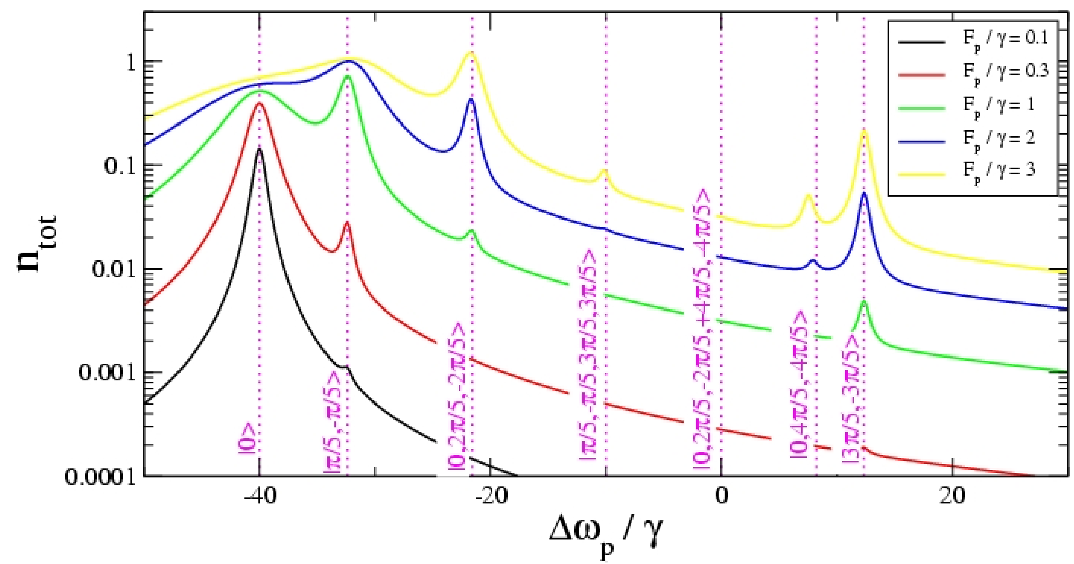
Example: two-particle states $\psi(i_1, i_2) = \frac{1}{\sqrt{2}\,L} \sin\left(\frac{(2n+1)\pi}{L} |i_1 - i_2|\right)$

M. D. Girardeau, Phys. Rev. **1**, 516 (1960)

Impenetrable “fermionized” photons in 1D necklaces

Many-body eigenstates of
Tonks-Girardeau gas
of impenetrable photons

Coherent pump
selectively addresses
specific many-body states



Transmission spectrum as a function pump frequency for fixed pump intensity:

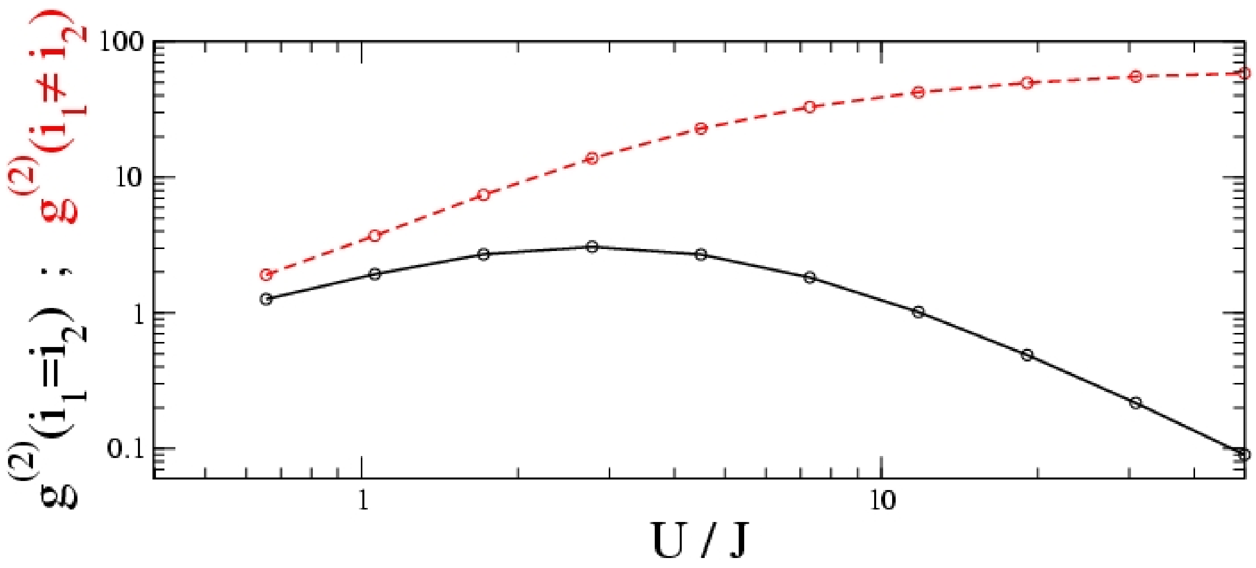
- each peak corresponds to a Tonks-Girardeau many-body state $|q_1,q_2,q_3\ldots\rangle$
- q_i quantized according to PBC/anti-PBC depending on N=odd/even
- U/J >> 1: efficient photon blockade, impenetrable photons.

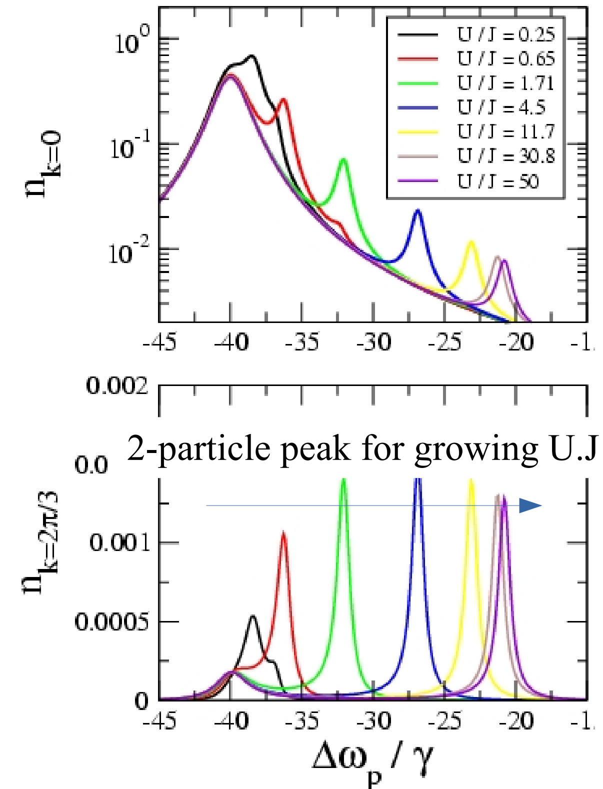
N-particle state excited by N photon transition:

- Plane wave pump with k_p=0: selects states of total momentum P=0
- Monochromatic pump at ω_p: resonantly excites states of many-body energy E such that ω_p= E / N

IC, D. Gerace, H. E. Türeci, S. De Liberato, C. Ciuti, A. Imamoglu, PRL **103**, 033601 (2009)
See also related work D. E. Chang et al, Nature Physics (2008)

State tomography from emission statistics





Finite U/J, pump laser tuned on two-photon resonance

- intensity correlation between the emission from cavities i_1, i_2
- at large U/γ, larger probability of having N=0 or 2 photons than N=1
  - low U<<J: bunched emission for all pairs of i_1, i_2
  - large U>>J: antibunched emission from a single site
positive correlations between different sites
- Idea straightforwardly extends to more complex many-body states.

Photon blockade + synthetic gauge field = FQHE for light

Bose-Hubbard model: $$H_0 = \sum_i \hbar\omega_\circ \hat{b}_i^\dagger \hat{b}_i - \hbar J \sum_{\langle i,j \rangle} \hat{b}_i^\dagger \hat{b}_j e^{i\varphi_{ij}} + \hbar \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$

gauge field gives phase in hopping terms

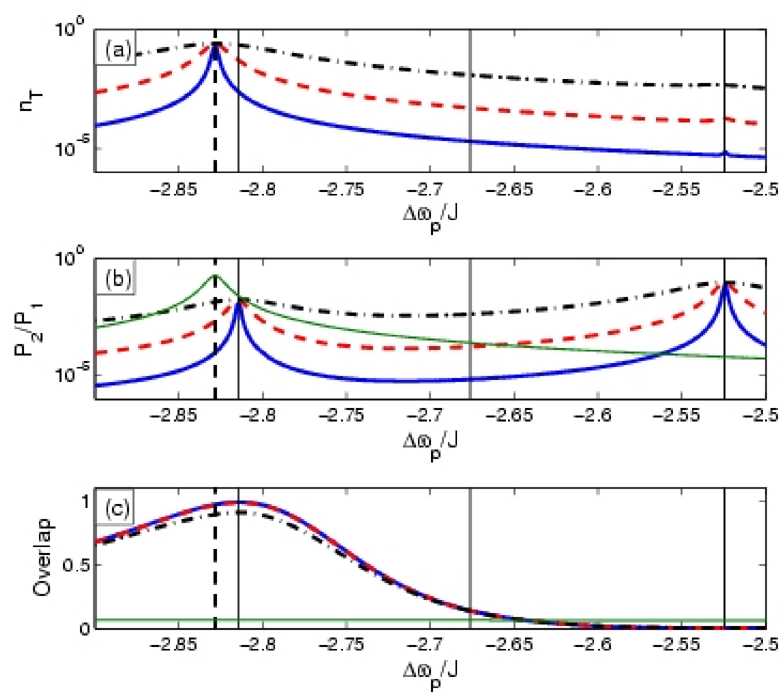
with usual coherent drive and dissipation → look for non-equil. steady state

Transmission spectra:

- peaks correspond to many-body states
- comparison with eigenstates of H_0
- good overlap with Laughlin wf (with PBC)

$$\psi_l(z_1, ..., z_N) = \mathcal{N}_L F_{\mathrm{CM}}^{(l)}(Z) e^{-\pi\alpha \sum_i y_i^2} \times \prod_{i<j}^{N} \left(\vartheta \begin{bmatrix} \frac{1}{2} \\ \frac{1}{2} \end{bmatrix} \left(\frac{z_i - z_j}{L} \middle| i \right) \right)^2$$

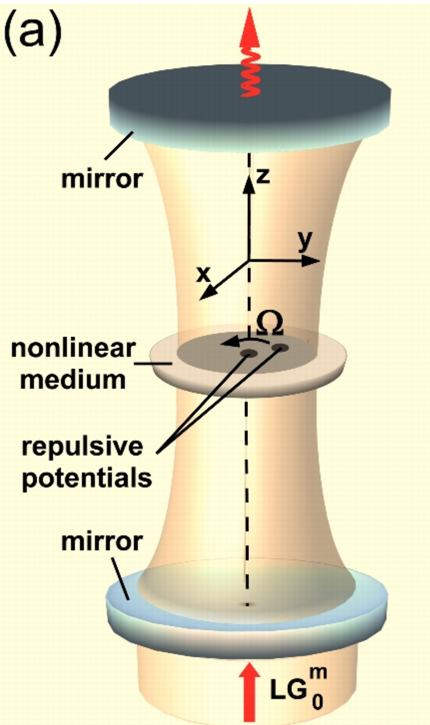
- no need for adiabatic following, etc....



R. O. Umucalilar and IC, *Fractional quantum Hall states of photons in an array of dissipative coupled cavities*, PRL 108, 206809 (2012)
See also related work by Cho, Angelakis, Bose, PRL 2008; Hafezi et al. NJP 2013; arXiv:1308.0225

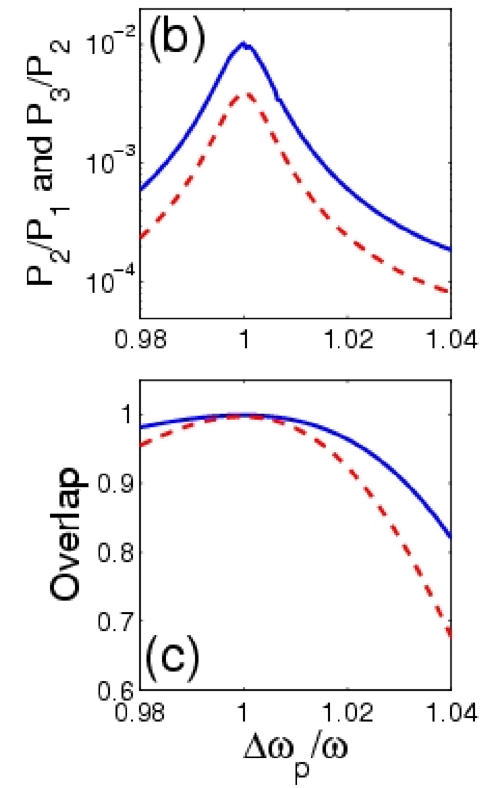
Continuous space FQH physics

Single cylindrical cavity. No need for cavity array



same form → Coriolis $F_c = -2m\Omega \times v$

→ Lorentz $F_L = e\, v \times B$



Photon gas injected by Laguerre-Gauss pump

with finite orbital angular momentum

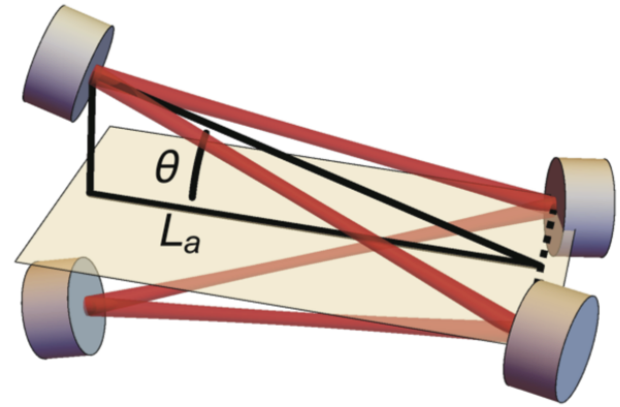
Strong repuls. interact., e.g. layer of Rydberg atoms

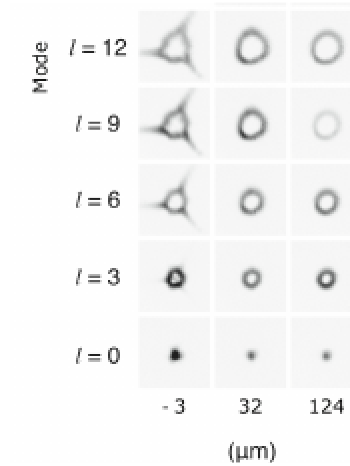
Resonant peak in transmission due to Laughlin state:

$$\psi(z_1,\ldots,z_N) = e^{-\sum_i |z_i|^2/2} \prod_{i<j} (z_i - z_j)^2$$

R. O. Umucalilar and IC, *Anyonic braiding phases in a rotating strongly correlated photon gas*, arXiv:1210.3070

Experiment @ Chicago





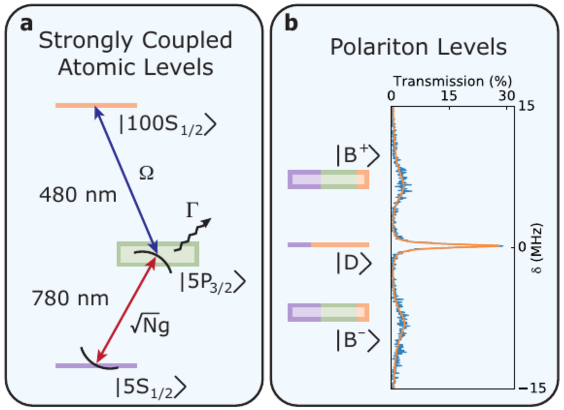
A far smarter design

Non-planar ring cavity:

- Parallel transport→ synthetic B
- Landau levels for photons observed

Crucial advantages:

- Narrow frequency range relevant
- Integrated with Rydberg-EIT reinforced nonlinearities



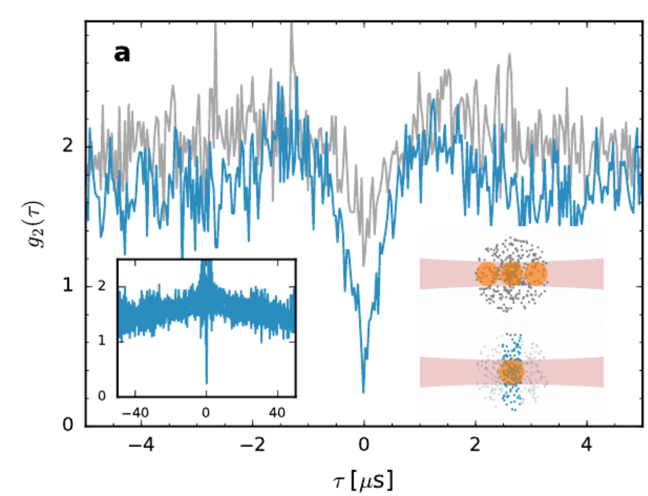
Polariton blockade on lowest (0,0) mode

- Equivalent to $\Delta_{\text{Laughlin}} > \gamma$

Easiest strategy for Laughlin

- Coherent pumping→ multi-photon peaks to few-body states
- Laughlin state → quantum correlations between orbital modes

(Umucalilar-Wouters-IC, PRA 2014)



Breaking news: 2-photon Laughlin state realized
(Clark et al., Nature 2020)

Figures from J. Simon's group @ U. Chicago
Schine et al., Nature 2016; Jia et al. 1705.07475

Experiment @ Chicago (II)

PHYSICAL REVIEW A **89**, 023803 (2014)

Probing few-particle Laughlin states of photons via correlation measurements

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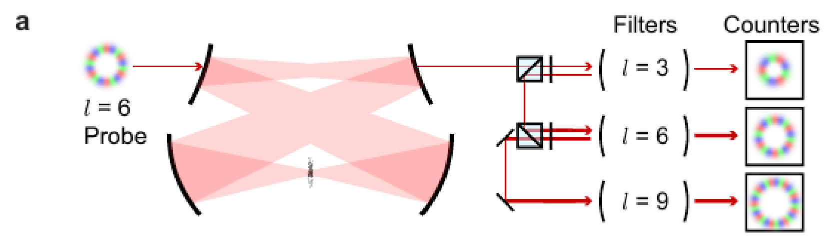
(Received 29 November 2013; published 5 February 2014)

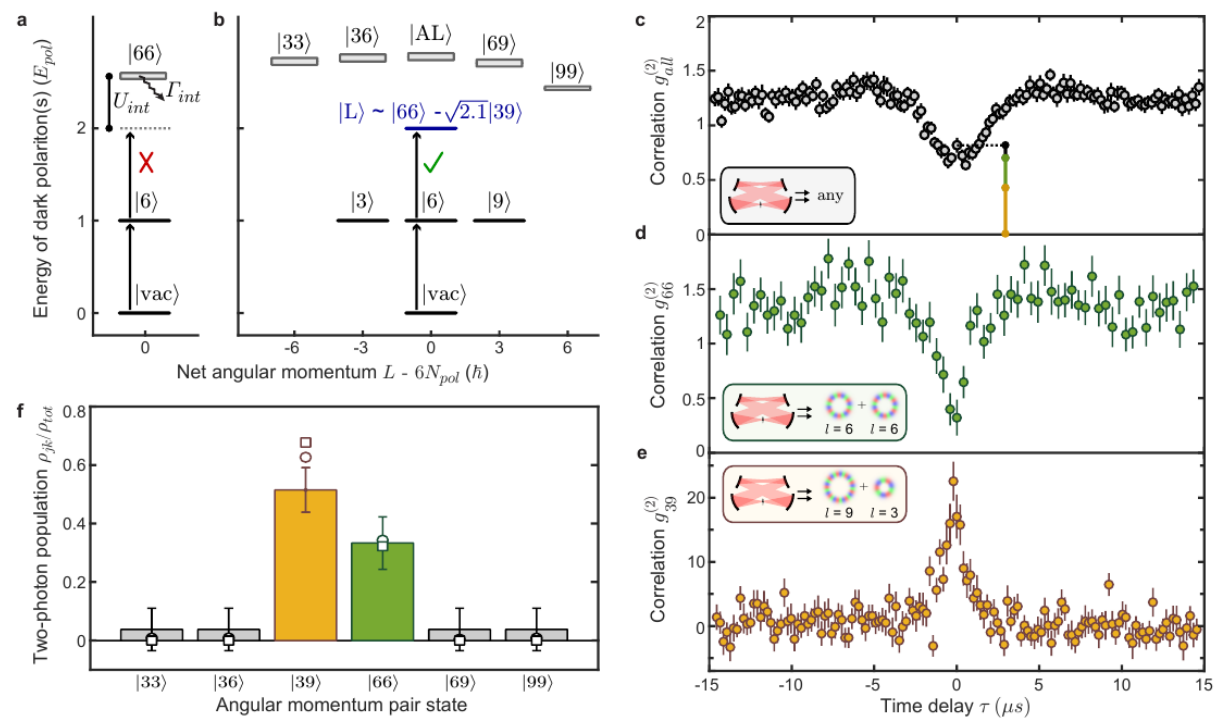
We propose methods to create and observe Laughlin-like states of photons in a strongly nonlinear optical cavity. Such states of strongly interacting photons can be prepared by pumping the cavity with a Laguerre-Gauss beam, which has a well-defined orbital angular momentum per photon. The Laughlin-like states appear as sharp resonances in the particle-number-resolved transmission spectrum. Power spectrum and second-order correlation function measurements yield unambiguous signatures of these few-particle strongly correlated states.



Quantum optical tricks
to highlight generation
of two-photon
Laughlin state

Challenge: scale up to larger
number of particles

Coherent pump scheme scales
very bad with N for topological
states

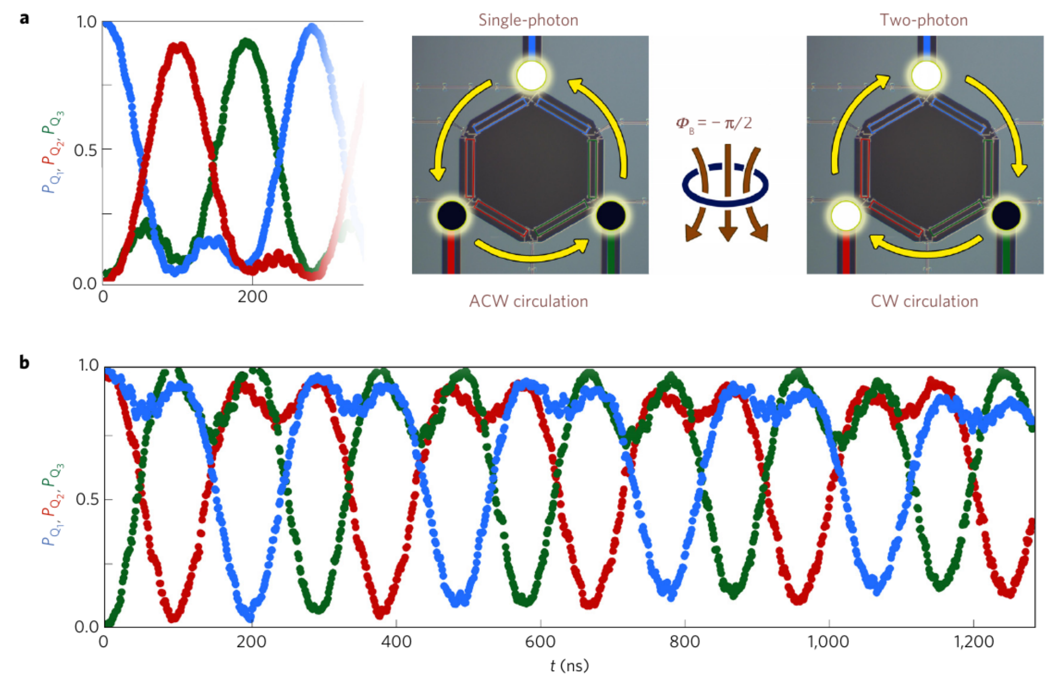


L. W. Clark, N. Schine, C. Baum, N. Jia, J. Simon, *Observation of Laughlin states made of light*, Nature 2020

Conservative dynamics in circuit-QED experiment: interplay of strong interactions & synthetic magnetic field

Ring-shaped array of qubits in a superconductor-based circuit-QED platform

- Transmon qubit: two-level system
  → Impenetrable microwave photons
- Time-modulation of couplings
  → synthetic gauge field



Roushan et al., Nat. Phys. 2016

- Independently initialize sites
- Follow unitary evolution until bosons lost
  (microwave photons → long lifetime)
- Monitor site occupation in time

"Many"-body effect:

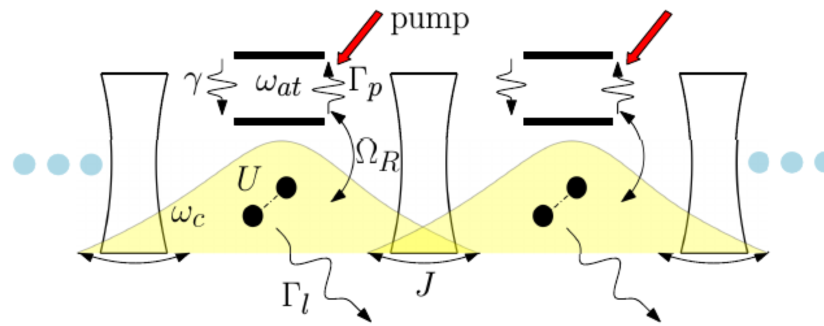
two-photon state → opposite rotation compared to one-photon state

(similar to cold-atom experiment in Greiner's lab: Tai et al., Nature 2017)

How to access larger particle numbers

Coherent pump only able to selectively excite few-photon states

→ Frequency-dependent incoherent pumping, e.g. collection of inverted emitters

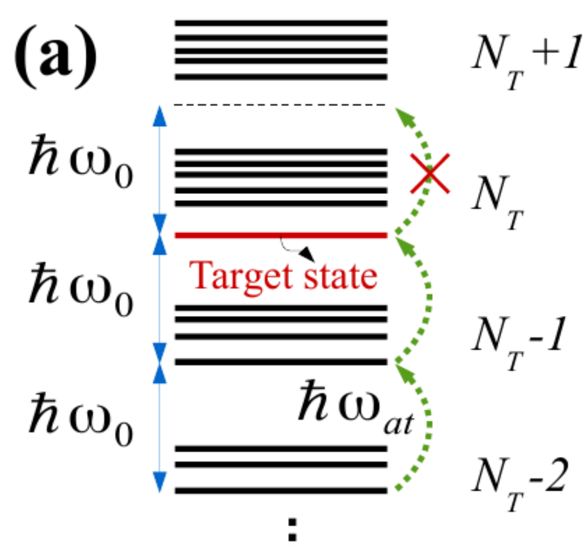


- Lorentzian emission line around ω_{at}
  sophisticated schemes → other spectral shapes

- Emission only active if many-body transition
  is near resonance

- Injects photons until band is full (MI) or
  many-body gap develops (FQH)

- Many-body gap blocks excitation of higher states



Umucalilar-IC, PRA 2017
Lebreuilly, Biella et al., PRA 2017

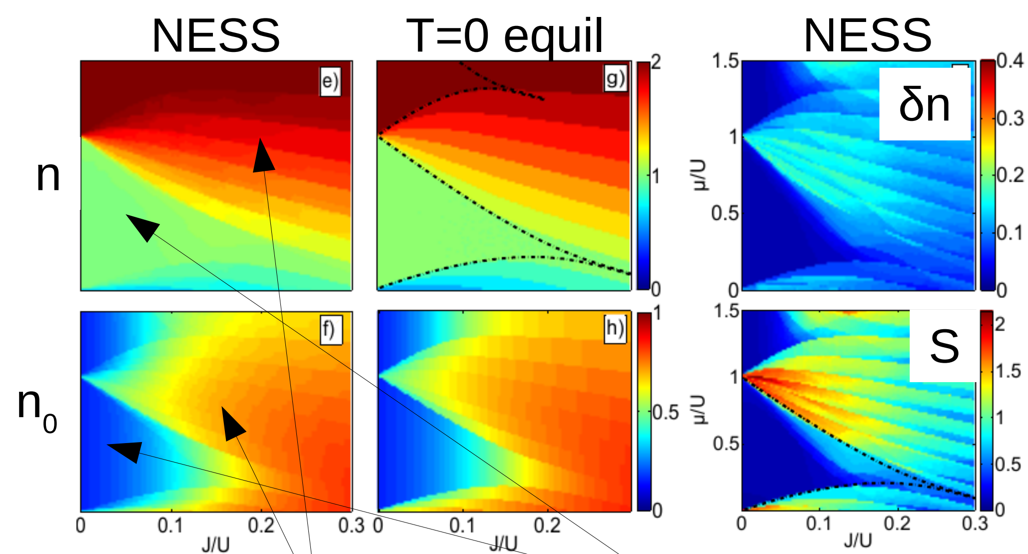
General idea:
Kapit, Hafezi, Simon, PRX 2014
Lebreuilly et al. CRAS (2016)

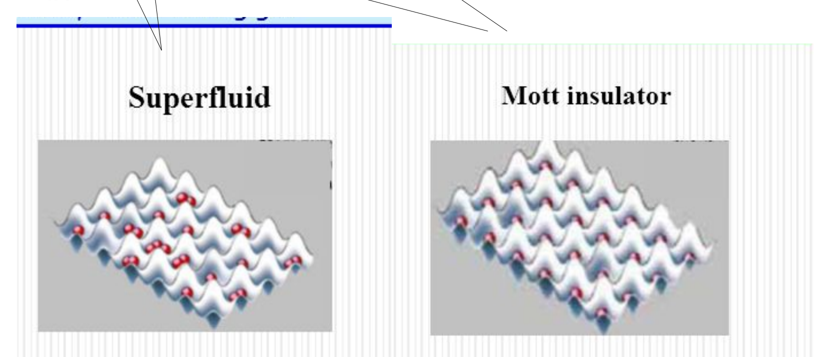
Mott insulators of light

- non-Markovian master equation:
  frequency-dependent emission
  → rescaled jump operators
- driven-dissipative steady state stabilizes
  strongly correlated many-body states
  e.g. Mott-insulator, FQH…
- resembles low-T equilibrium
  (but interesting deviations in some cases)
- (in principle) no restriction to small N_{ph}
  only requirement → many-body energy gap

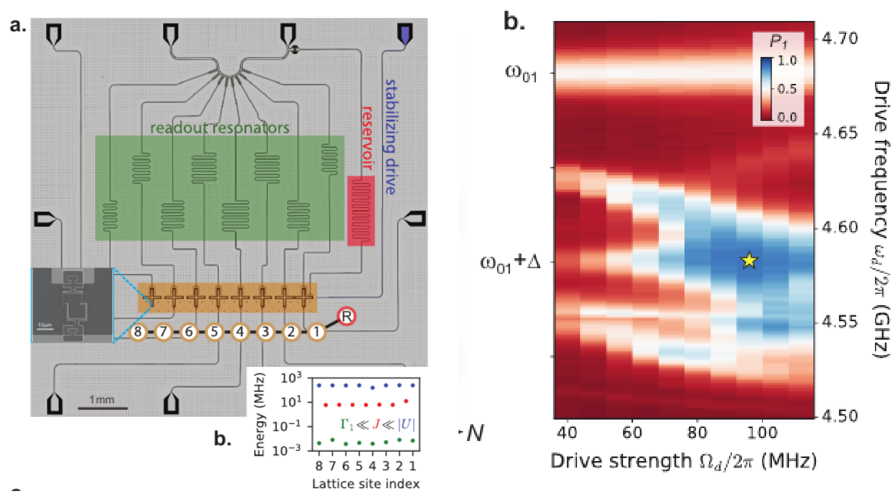
$$\bar{\mathcal{L}}_{\mathrm{em}}(\rho_{\mathrm{ph}}) = \frac{\Gamma_{\mathrm{em}}}{2}\sum_{i=1}^{k}\left[2\bar{a}_i^{\dagger}\rho_{\mathrm{ph}}\bar{a}_i - \bar{a}_i\bar{a}_i^{\dagger}\rho_{\mathrm{ph}} - \rho_{\mathrm{ph}}\bar{a}_i\bar{a}_i^{\dagger}\right]$$

$$\langle f'|\bar{a}_i^{\dagger}|f\rangle = \frac{\Gamma_{\mathrm{pump}}/2}{\sqrt{(\omega_{\mathrm{at}}-\omega_{f',f})^2+(\Gamma_{\mathrm{pump}}/2)^2}}\langle f'|a_i^{\dagger}|f\rangle$$





Lebreuilly, Biella et al., 1704.01106 & 1704.08978
(published on PRA, 2017)



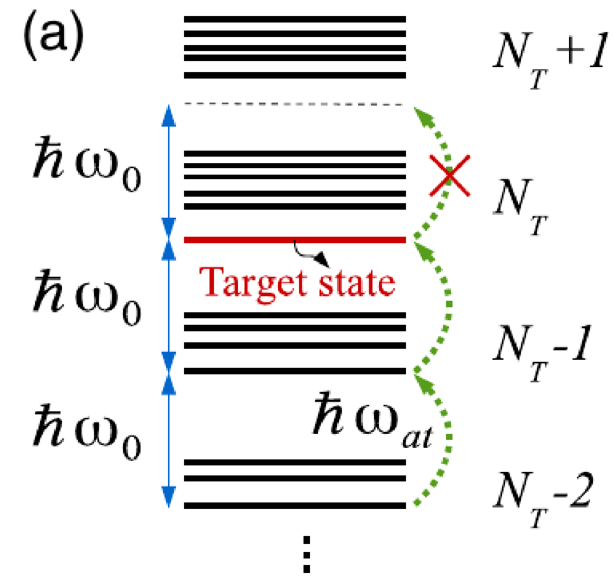
First expt: Ma *et al.* Nature 2019

Related work in Kapit, Hafezi, Simon, PRX 2014

What about large FQH fluids?

Coherent pump:

- Able to selectively generate few-body states
- Limited by (exponentially) decreasing matrix element for larger systems

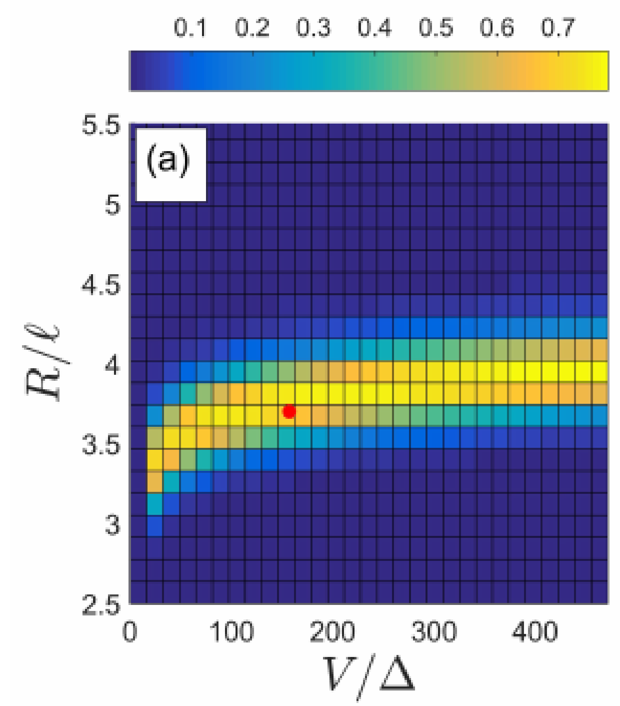


Frequency-dependent incoherent pump:

- Interactions → many-body gap Δ
- Edge excitations not gapped. Hard-wall confinement gives small δ
- Non-Markovianity blocks excitation to higher states

Calculations only possible for small systems:

- Large overlap with Laughlin states
- Excitations localized mostly on edge



Open question: what are ultimate limitations of this pumping method?

R. O. Umucalilar, IC, *Generation and spectroscopic signatures of a fractional quantum Hall liquid of photons in an incoherently pumped optical cavity*, PRA 2017.
R. O Umucalilar, J. Simon, IC, *Autonomous stabilization of photonic Laughlin states through angular momentum potentials*, PRA 2022
Kurilovich et al., *Stabilizing the Laughlin state of light: dynamics of hole fractionalization*, arXiv:2111.01157

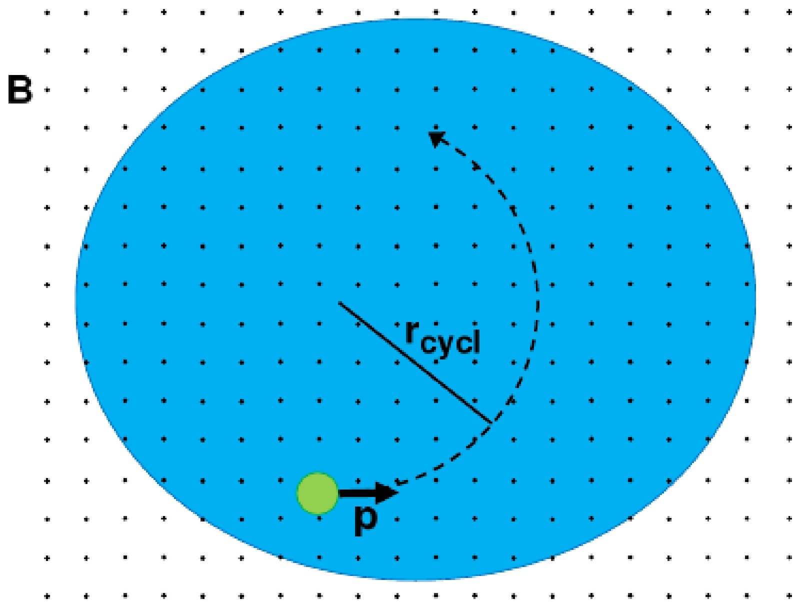
A long-term objective:

Probing anyonic statistics of quasi-holes

What is an anyon?
Quantum mechanics of anyons (I) – single particle

Laughlin wavefunction of Fractional Quantum Hall:

- quasi-holes → no E_{kin}, no independent life
- dressed by heavy impurity → anyonic molecule
- full-fledged mechanical degree of freedom



Born-Oppenheimer approx:

- Heavy impurity→ slow Degree of Freedom
- Light FQH particles → fast DoF

$$H_{\text{eff}} = \frac{\left[-i\nabla_{\mathbf{R}} - (Q - \nu q)\,\mathbf{A}(\mathbf{R})\right]^2}{2\mathcal{M}}$$

- Mass $\mathcal{M}$ → M (impurity) + QH dragging effect
- Impurity & FQH particles feel (Synth-)B,
  so synth-Charge → Q (impurity) – ν q (QH)

Cyclotron orbit → fractional charge and BO mass correction

A. Muñoz de las Heras, E. Macaluso, IC, PRX 2020

Quantum mechanics of anyons (II) – two particles

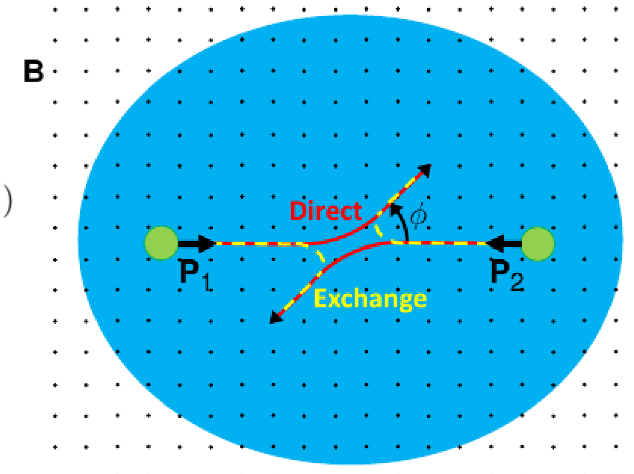
Each particle → attached flux

$$\mathcal{A}_j(\mathbf{R}) = \mathcal{A}_\mathrm{q}(\mathbf{R}_j) + \mathcal{A}_{\mathrm{stat},j}(\mathbf{R}) = \frac{\mathcal{B}_\mathrm{q}}{2}\mathbf{u}_\mathrm{z} \times \mathbf{R}_j + (-1)^j \frac{\nu}{R_\mathrm{rel}^2}\mathbf{u}_\mathrm{z} \times \mathbf{R}_\mathrm{rel}$$

Relative motion:

- inter-particle potential
- statistical A_{rel} due to attached flux

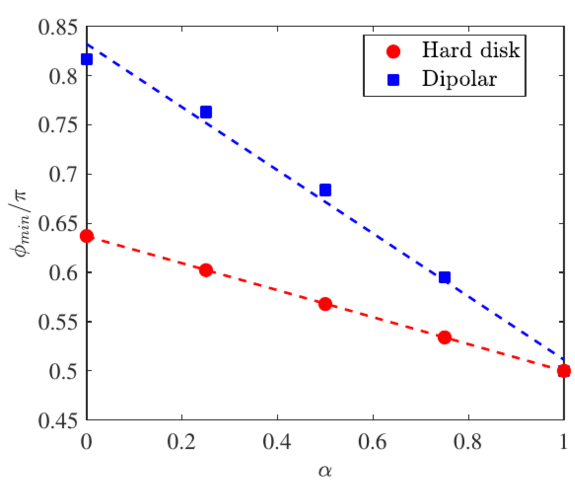
$$H_\mathrm{rel} = \frac{[\mathbf{P}_\mathrm{rel} + \mathbf{A}_\mathrm{rel}(\mathbf{R}_\mathrm{rel})]^2}{2\mathcal{M}_\mathrm{rel}} + V_\mathrm{ii}(R_\mathrm{rel})$$

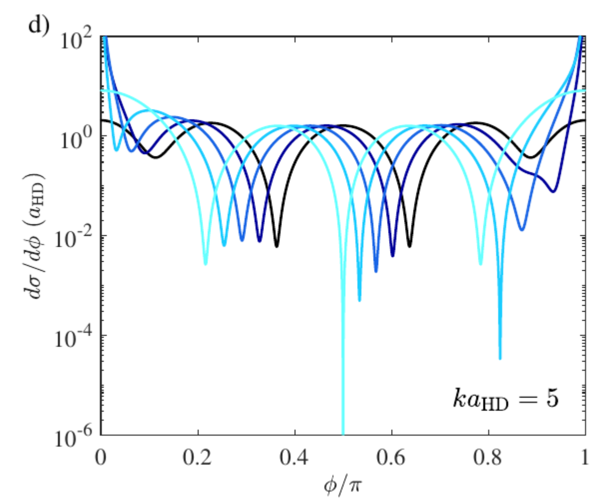


2-body scattering: interference of direct & exchange

- fringes in differential cross section
- fringe position depends on attached flux, i.e. measure fractional statistics

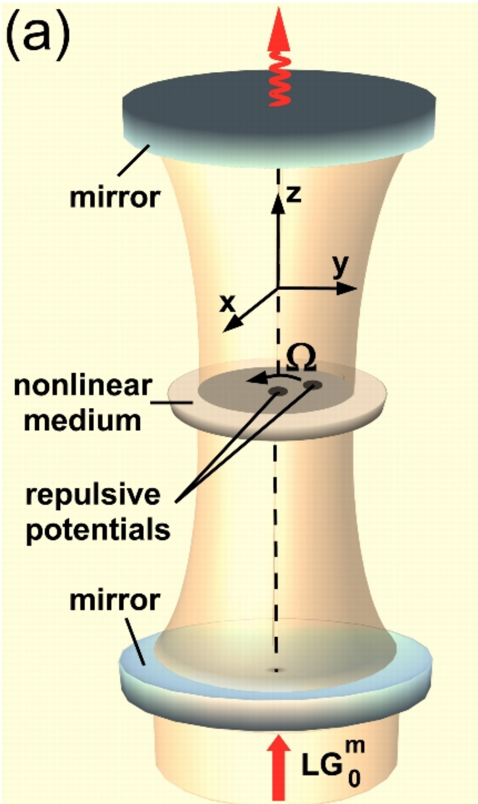
- Scheme works with polar molecules (heavy + long-range interactions) in atoms (light FQH gas)
- What about Rydberg polaritons?





A. Muñoz de las Heras, E. Macaluso, IC, PRX 2020

Optical signatures of the anyonic braiding phase



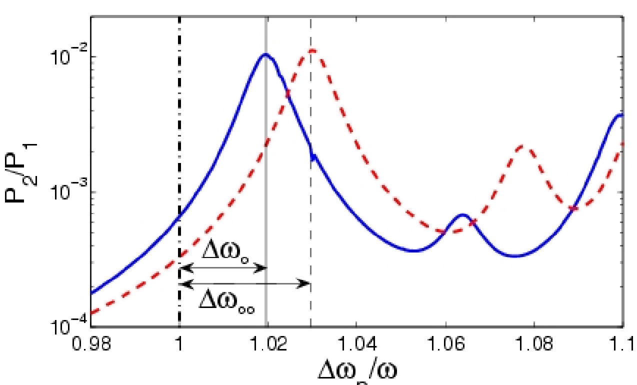
Anyonic statistics of quasi-holes: many-body Berry phase ϕ_{Br} when positions swapped during braiding

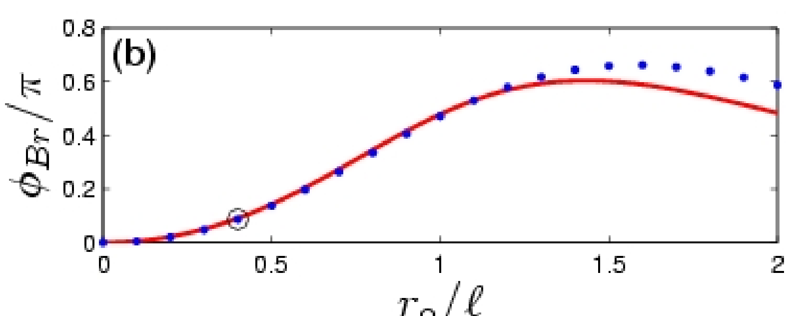
In a photonic system:

- LG pump to create and maintain quantum Hall liquid
- Localized repulsive potentials in trap:
  → create quasi-hole excitation in quantum Hall liquid
  → position of holes adiabatically braided in space
- Berry phase extracted from shift of transmission resonance while repulsive potential moved with period T_{rot} along circle

$$\phi_{Br} \equiv (\Delta\omega_{oo} - \Delta\omega_{o})\, T_{rot} \quad [2\,\pi]$$

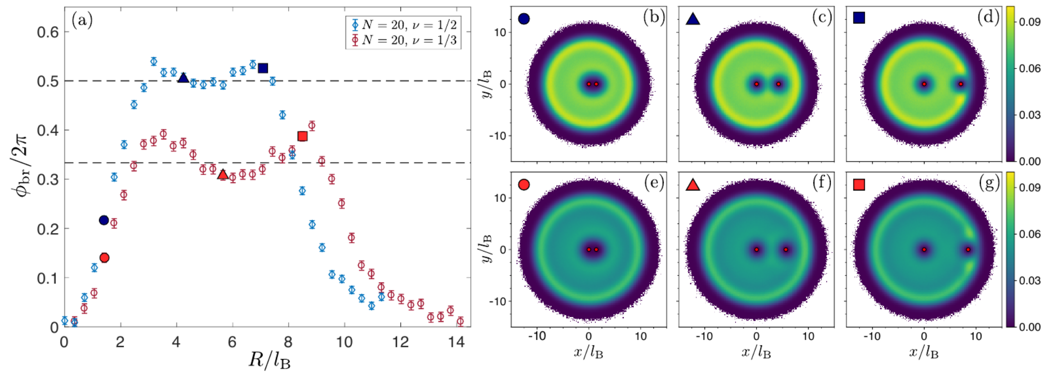
How to measure ϕ_{Br} without an actual braiding?





R. O. Umucalilar and IC, *Anyonic braiding phases in a rotating strongly correlated photon gas*, arXiv:1210.3070

A simpler strategy: observing anyonic statistics in ToF measurements



Braiding phase → Berry phase when two quasi-holes are moved around each other

$$\varphi_{\mathrm{B}}(R) = i \oint_R \langle \Psi(\theta) | \partial_\theta | \Psi(\theta) \rangle d\theta.$$

Braiding operation can be generated by rotations, so braiding phase related to L_z

$$\varphi_{\mathrm{B}}(R) = \frac{1}{\hbar} \oint_R \langle \Psi(\theta) | L_z | \Psi(\theta) \rangle d\theta = \frac{2\pi}{\hbar} \langle L_z \rangle$$

Self-similar expansion of lowest-Landau-levels → L_z can be measured in time-of-flight via size of the expanding cloud

$$\langle r^2 \rangle_{\mathrm{tof}} = \frac{1}{N} \left(\frac{\hbar t}{\sqrt{2} M l_B} \right)^2 \left(\frac{\langle L_z \rangle}{\hbar} + N \right) = \left(\frac{\hbar t}{2 M l_B^2} \right)^2 \langle r^2 \rangle$$

Can be applied to both cold atoms or to fluids of light looking at far-field emission pattern
Difficulty → small angular momentum difference of QH compared to total L_z

Umucalilar, Macaluso et al., *Observing anyonic statistics via time-of-flight measurements*, PRL (2018)

Quasi-Hole structure vs. anyon statistics (I)

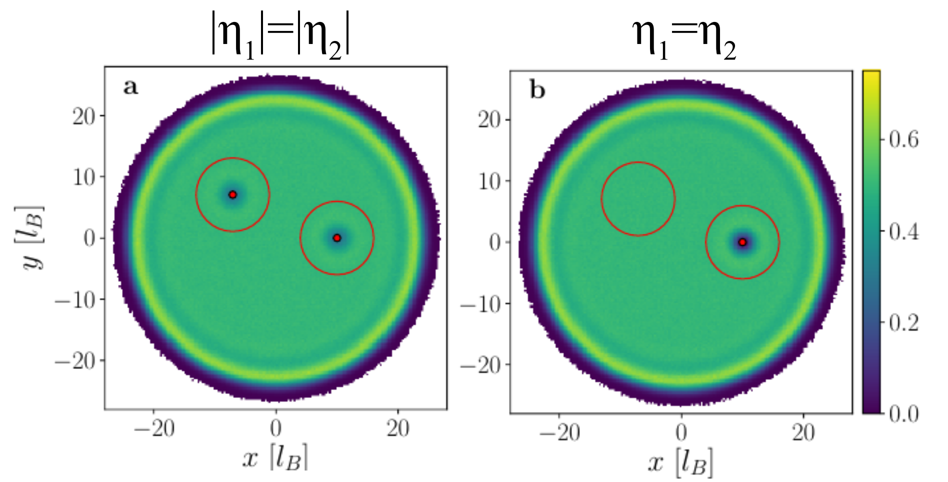
- Compare (two) single quasi-holes and
  overlapping pair of quasi-holes:

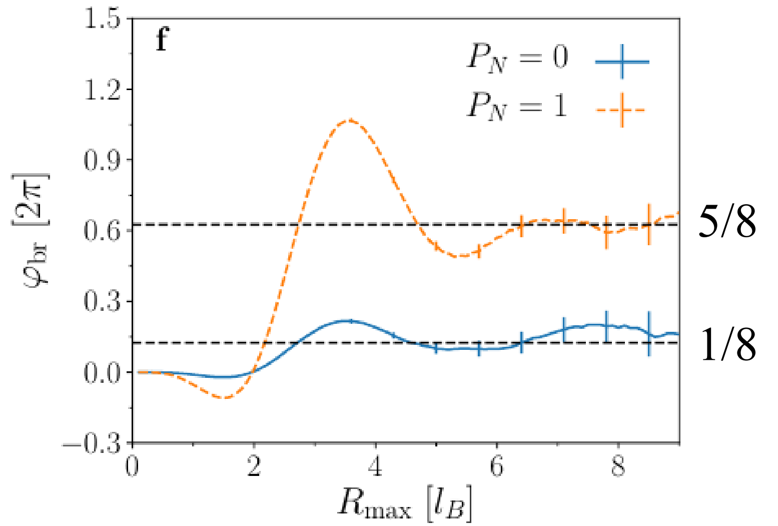
$$\frac{\varphi_{\mathrm{br}}}{2\pi} = \frac{1}{\hbar}\left[\langle \hat{L}_z \rangle_{|\eta_1|=|\eta_2|} - \langle \hat{L}_z \rangle_{\eta_1=\eta_2}\right].$$

- Relates to difference of density profiles:

$$\frac{\varphi_{\mathrm{br}}}{2\pi} = \frac{N}{2l_B^2}\left[\langle r^2 \rangle_{|\eta_1|=|\eta_2|} - \langle r^2 \rangle_{\eta_1=\eta_2}\right],$$

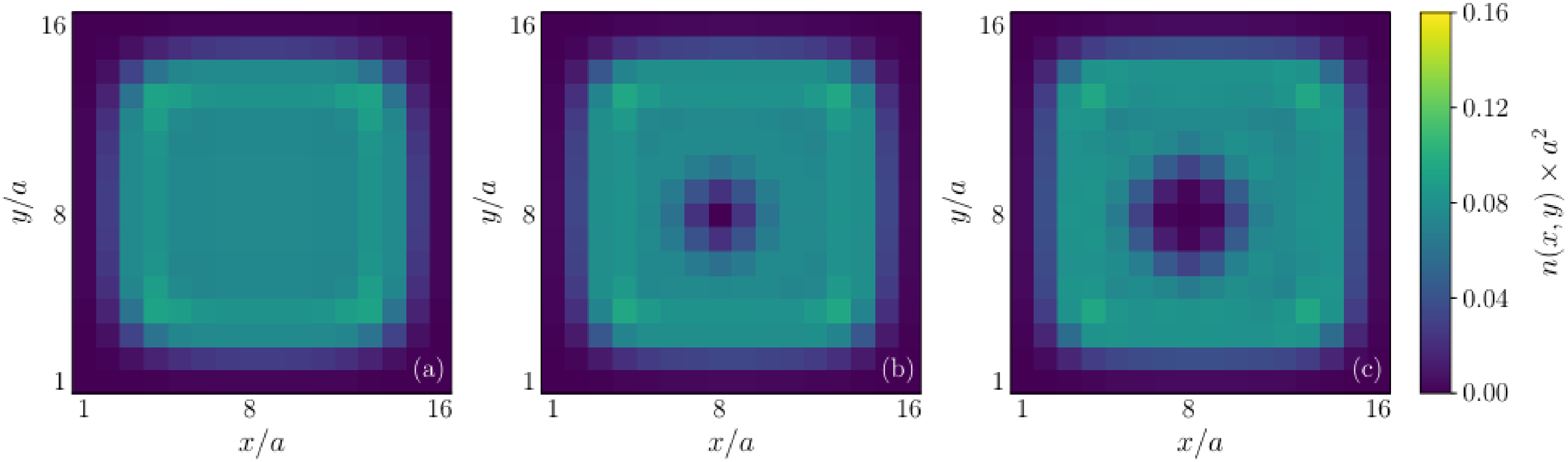
- Incompressibility → external region unaffected
- Statistics inferred from local density difference around QH core, i.e. variance of density depletion
- Insensitive to spurious excitation of (ungapped) edge states
- Proposal realizable in Chicago's twisted cavity set-up
- Numerical calculation using Moore-Read wavefunction allows to distinguish fusion channels of even/odd
  total particle number





E. Macaluso, T. Comparin, L. Mazza, IC, *Fusion channels of non-Abelian anyons from angular-momentum and density-profile measurements*, PRL 2019

Quasi-Hole structure vs. anyon statistics (II)



N	L	α	Ω/t
12	16	0.15	1×10^{-3}

Discrete lattice model → Harper-Hofstadter-Bose-Hubbard

Ground state using Tree-Tensor-Network ansatz

- experimentally realistic “large” system
- open boundary conditions with harmonic trap
- repulsive potentials to pin quasi-holes

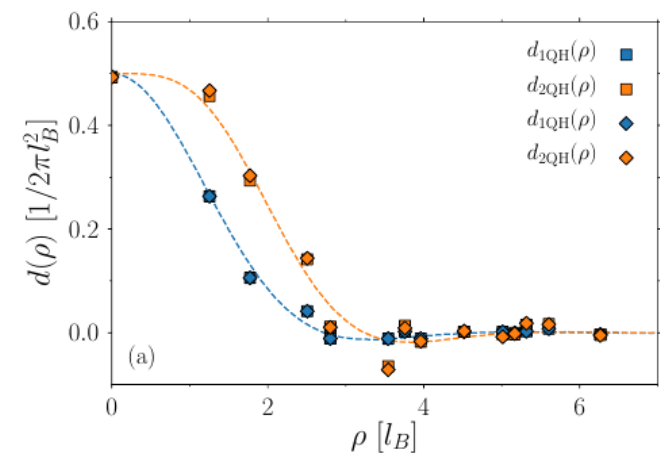
Apply discretized version of braiding phase formula

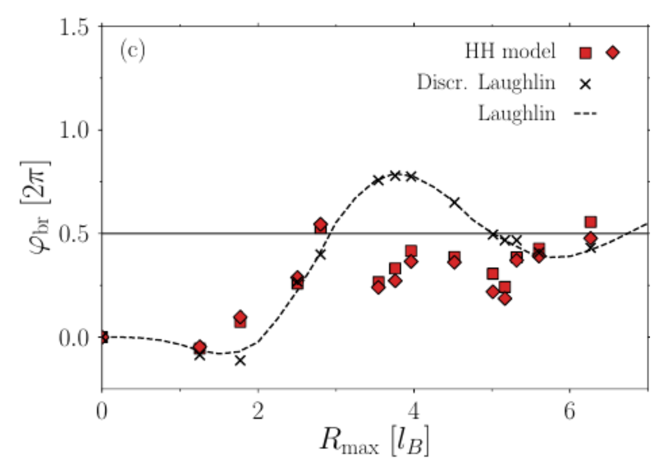
$$\frac{\varphi_{\mathrm{br}}}{2\pi} = \frac{N}{2l_B^2}\left[\langle r^2\rangle_{|\eta_1|=|\eta_2|} - \langle r^2\rangle_{\eta_1=\eta_2}\right],$$

to physical ground state wavefunction

→ Accurate reconstruction of anyonic statistics

→ Experiment accessible in state-of-the-art circuit-QED systems





E. Macaluso *et al.*, *Charge and statistics of lattice quasiholes from density measurements: a Tree Tensor Network study,* Phys. Rev. Research (2020)

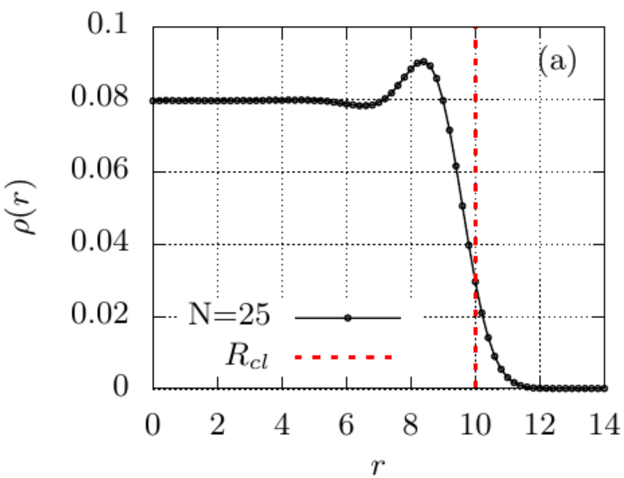
On-going work:

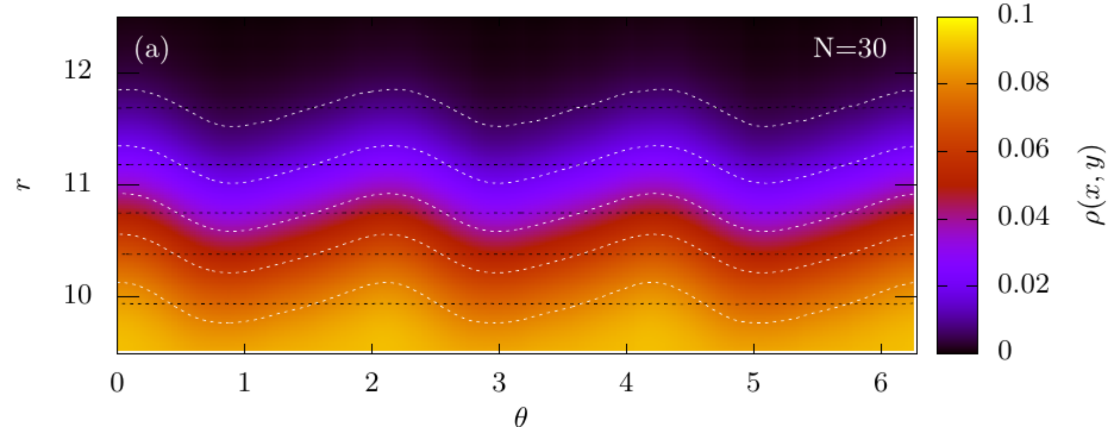
Linear and nonlinear edge dynamics of FQH clouds

Chiral Luttinger liquids and beyond

- A. Nardin, IC, Non-linear edge dynamics of an integer quantum Hall fluid, Europhys. Lett. 132, 10002 (2020).
- A. Nardin, IC, *Linear and nonlinear edge dynamics of trapped fractional quantum Hall droplets beyond the chiral Luttinger liquid paradigm*, arXiv:2203.02539
- Z. Bacciconi, *Fractional quantum Hall edge dynamics from a quantum optics perspective*,
  MSc thesis at UniTrento (2021); arXiv:2111.05858

Response of trapped FQH cloud to external potential (I)



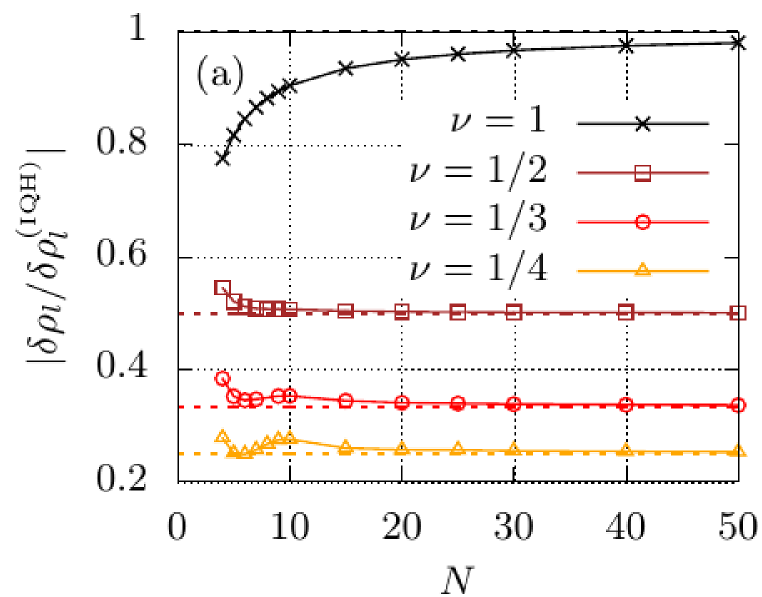


Trapping potential $V_{conf}(r) = \lambda\, r^{\delta}$

Ab initio ED calculations by MC evaluation of matrix elements via Metropolis (upto ~50 particles)

Time-dependent perturbation $U(r,\theta;t)$:

- generates oscillatory perturbation on edge

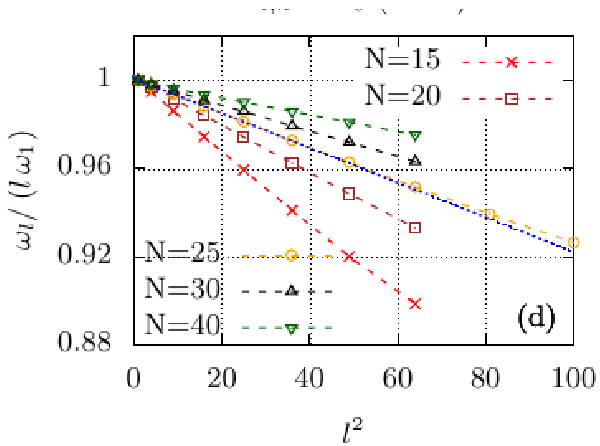


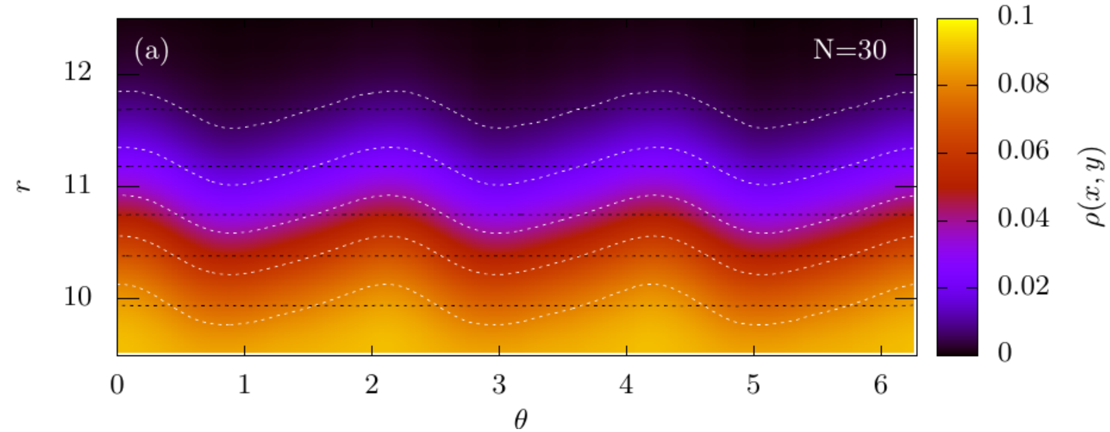
Weak perturbation → chiral Luttinger liquid behaviour

- linear response proportional to filling ν
- related to quantized transverse conductivity of FQH
- matches with numerics for long wavelength excitations...

A. Nardin, IC, *Linear and nonlinear edge dynamics of trapped fractional quantum Hall droplets beyond the chiral Luttinger liquid paradigm*, arXiv:2203.02539

Response of trapped FQH cloud to external potential (II)





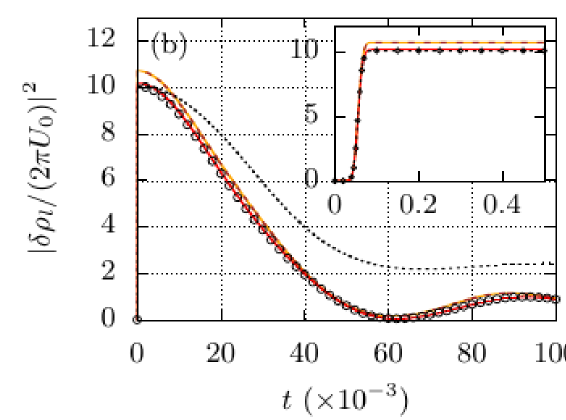
Linear response matches χLL...but much more physics hidden in edge perturbation σ(z,t) :

- free oscillation frequency shift ~ k^3 → group velocity dispersion
- nonlinear effects → frequency shift proportional to amplitude σ (due to radially increasing trapping force)

Well captured by classical evolution eq: driven Korteweg-de Vries

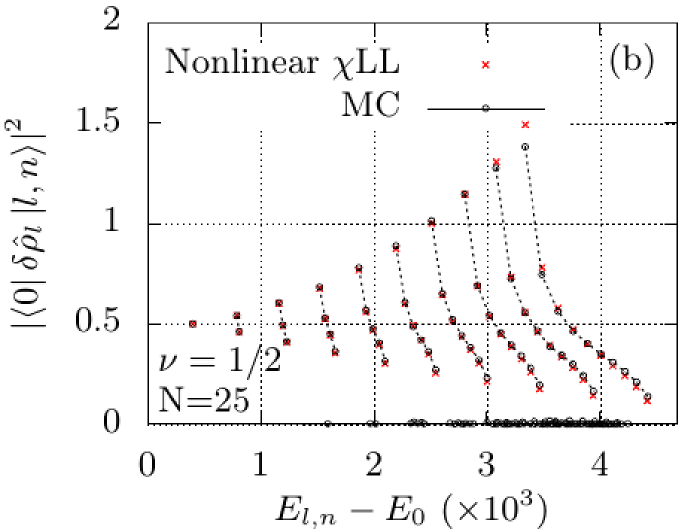
$$\frac{\partial \sigma}{\partial t} = -\left[v_0 + \frac{2\pi\tilde{c}_0}{\nu}\sigma\right]\frac{\partial \sigma}{\partial \zeta} - \beta_m \tilde{c}_0 \frac{\partial^3 \sigma}{\partial \zeta^3} - \frac{\nu}{2\pi}\frac{\partial U}{\partial \zeta}$$

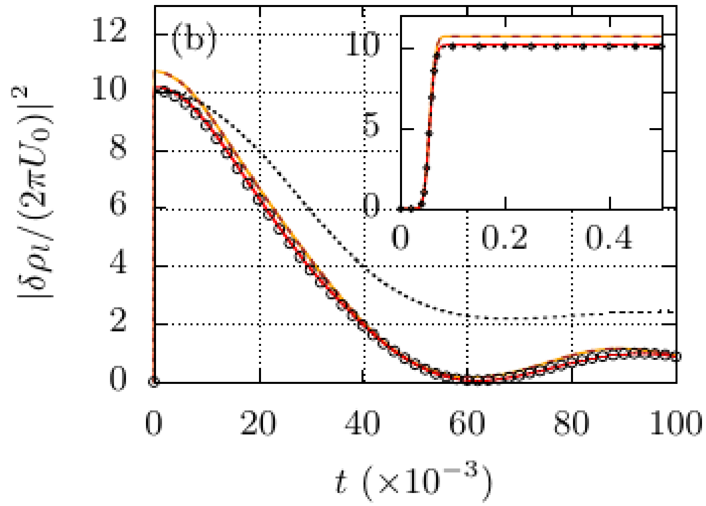
- but also shows temporal decay of oscillation… ...which requires further refinements...

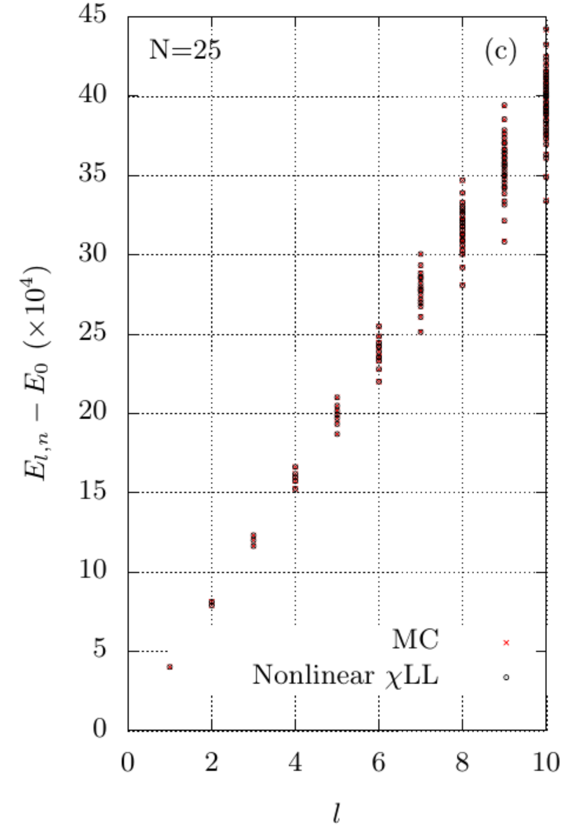


A. Nardin, IC, *Linear and nonlinear edge dynamics of trapped fractional quantum Hall droplets beyond the chiral Luttinger liquid paradigm*, arXiv:2203.02539

Response of trapped FQH cloud to external potential (III)







Broadening associated to damping captured by quantum-χLL

$$\hat{H}^{NL}_{\chi\mathrm{LL}} = \int d\zeta \left[\frac{\pi\, v_0}{\nu}\,\hat{\sigma}^2 - \frac{\pi\,\beta_m \tilde{c}_0}{\nu}\left(\frac{\partial\hat{\sigma}}{\partial\zeta}\right)^2 + \frac{2\pi^2\tilde{c}_0}{3\nu^2}\hat{\sigma}^3 + U(\zeta,t)\,\hat{\sigma}\right]$$

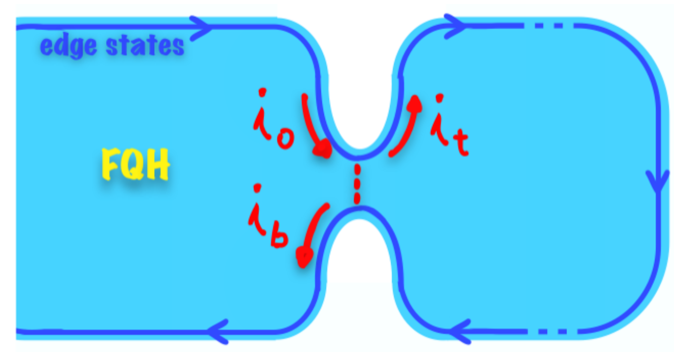
with $\quad [\hat{\sigma}(\zeta), \hat{\sigma}(\zeta')] = -i\,\frac{\nu}{2\pi}\,\partial_\zeta\delta(\zeta-\zeta').$

Quantum-χLL eigenstates well match ED results, as well as temporal evolution of observables

Dynamic structure factor shape → going to be explained in terms of refermionization of LL

A. Nardin, IC, *Linear and nonlinear edge dynamics of trapped fractional quantum Hall droplets beyond the chiral Luttinger liquid paradigm*, arXiv:2203.02539

(Preliminary) Quantum dynamics at constriction



χLL dynamics of edge + intrinsic nonlinearity at junction

quasi-particle tunneling H_{int}~exp[i (φ(0)-φ(l))]+ h.c.

→ Complex nonlinear dynamics

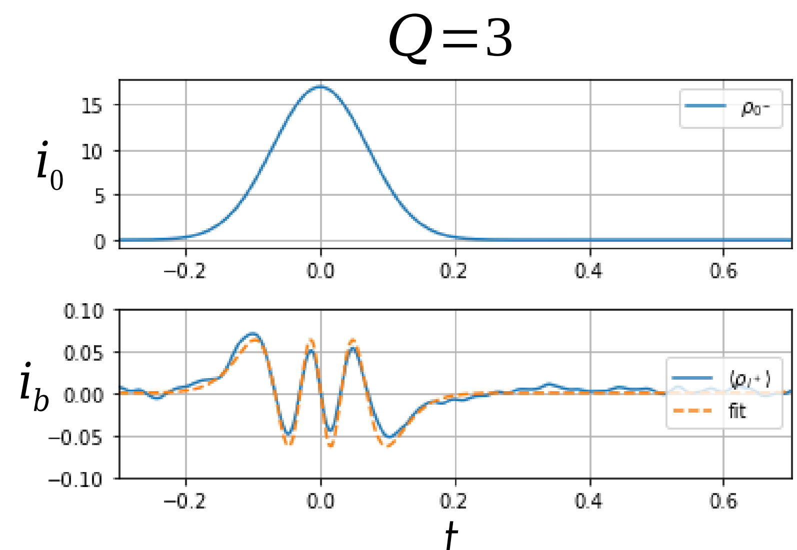
$$\partial_t \rho_s(x,t) + v\,\partial_x \rho_s(x,t) = -\Gamma \sin(2\pi q_s(t))\,(\delta(x) - \delta(x-l))$$

Truncated-Wigner description of bosonic χLL: classical noise describes quantum statistics

$$\rho_s(x,t=0) = \sum_{k>0} r_k \alpha_k e^{ikx} + h.c. \qquad \langle \rho_s(0^-,0)\,\rho_s(0^-,t)\rangle \propto -\frac{1}{mt^2}$$

Reproduces many features of FQH edge dynamics:

- Crystallization of high-charge wavepackets
- Gives hints of fractional shot-noise in current
- Better performance for large 1/ν: fractional charge ν of FQH makes semi-classical picture more accurate



Z. Bacciconi, *Fractional quantum Hall edge dynamics from a quantum optics perspective*, MSc thesis at UniTrento (2021); arXiv:2111.05858
Z. Bacciconi, A. Nardin, IC, in preparation (2022)

If you wish to know more...

BEC

REVIEWS OF MODERN PHYSICS, VOLUME 85, JANUARY–MARCH 2013

Quantum fluids of light

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I. Carusotto, C. Ciuti, Rev. Mod. Phys. **85**, 299 (2013)

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nature physics FOCUS | REVIEW ARTICLE
https://doi.org/10.1038/s41567-020-0815-y

Check for updates

Photonic materials in circuit quantum electrodynamics

Iacopo Carusotto[1], Andrew A. Houck[2], Alicia J. Kollár[3,4], Pedram Roushan[5], David I. Schuster[6,7] and Jonathan Simon[6,7]

Review article on Nature Physics (2020)

REVIEWS OF MODERN PHYSICS, VOLUME 91

Topological photonics

Review article arXiv:1802.04173 by Ozawa, Price, Amo, Goldman, Hafezi, Lu, Rechtsman, Schuster, Simon, Zilberberg, IC, RMP **91**, 015006 (2019)

Non-equilibrium Bose–Einstein condensation in photonic systems

Jacqueline Bloch[1], Iacopo Carusotto[2] and Michiel Wouters[3]

Review article on Nat. Rev. Phys. (2022)

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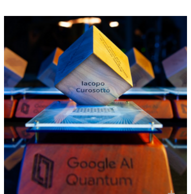

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PhoQuS Photons for Quantum Simulation

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